Secondary Beams at GANIL

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Abstract : GANIL, a user's facility since 1983, can deliver a broad spectrum of heavy-ion beams, from He to U, to well-equipped experimental areas. Their very large intensities are to be exploited to produce secondary beams, either using the fragmentation method (beams at energy per nucleon larger than 30 MeV/u), or the ISOL method. With the latter one, these ions have to be re-accelerated. The project of a cyclotron as a post-accelerator is described.

1. Introduction

Since the very first times of its operation, GANIL has been a users' facility, largely open to the nuclear physics community. The accelerator has provided physicists with intermediate energy (from 25 to 95 MeV/nucleon) heavy-ion beams, the optical qualities of which are well-known. From the first experiments at GANIL, fragmentation reaction have been used to produce several dozens of new elements and study such exotic nuclei. Such a research made use of the very large intensities obtained through the whole accelerator system of GANIL. It was realized that these very intense beams could be used to also produce exotic nuclei at rest, in thick targets, and to adapt the ISOL method to primary **heavy ion** beams. This program is now under consideration, with the project of a post-accelerator and a strong effort of research and development concerning the production and ionization for secondary elements. In the experimental areas, several versatile detectors built for the first eleven years of GANIL'S operation could provide an unvaluable contribution to the study of exotic nuclei. In particular, large efficiency 4 π-multidetectors will be useful in physical situations where the counting rate is going to be rather small, and spectrometers could help in solving identification problems. This project will represent a new opportunity, open to the international community, to what was once called a "renaissance" of nuclear structure studies.

2. Towards higher intensities

Obviously, such a program can only be conducted if the primary accelerator is able to deliver very intense beams. To increase the GANIL intensity has been a constant concern during the last years.

The injection system in the large cyclotron has been modified[1] and adapted to the current, very efficient ECR sources. The result was a much favorable curve of the energy per nucleon as a function of the accelerated ion mass (29 MeV/nucleon Pb, 25 MeVnucleon U). Following new developments on these ion sources and higher frequency of the R.F. injected in the plasma, the charge distribution of the produced ions is strongly shifted upwards and rather high charge states are reached. A major - and recent - modification[2] of the acceleration system has been the setting up of the 14 GHz ECR-4 ion source upon a high-voltage (100 kV) platform ; at the entrance of the injection cyclotron, the ions are given a velocity large enough that the very high space charge at the centre of the cyclotron will not limit the transmission of the machine. The optics of the injection line has been studied so that a maximum decoupling of the various motions is reached, and the injector transmission is increased to values as high as 60 or 70 %. The first part of this operation has already been completed and it ensures that more than 2.10^{13} particules can be accelerated. The second part of it has to do with safety procedures at these powers, any beam loss can be dangerous for the vacuum system. A buncher will be necessary for better injection in the second separated-sector cyclotron, and better controls will monitor the beam all along its path. This part remains to be done. An exemple of what is waited for after each phase of the operation can be found on the Table 1.

Table 1
Expected beam intensities for some ions after the two phases of the increases intensity operation (O.A.I.)

Ion	Energy (MeV/u)	Maximum Intensity in L3 (pps)		
		1990	After OAI 1	After OAI 2
$^{16}O^{4+/8+}$	95	1.5 10^{12}	1.6 10^{12}	3.8 10^{13}
$^{84}Kr^{14+/33+}$	60	5 10^{11}	5 10^{11}	>1.5 10^{12}
$^{129}Xe^{18+/44+}$	44	1.1 10^{11}	4.4 10^{11}	>5.0 10^{11}
$^{208}Pb^{23+/56+}$	29	5 10^{9}	4 10^{10}	>9.5 10^{10}
238U24+/59+	24	6.8 10^{8}	1.5 10^{10}	3 10^{10}
		Measured	Predicted	Predicted

As it is clear from this table, the main interest of the first step of this modification is found for the heaviest elements. The second one will bring the GANIL beams to intensity values of several 10^{13} particles per second for light ions.

3. The fragmentation method

Intermediate-energy fragmentation (or at least, forward-peaked direct) reactions at GANIL have been very successful to produce very far-from-stability nuclei, allowing to map out the drip-line.

The LISE device[3] (Fig. 1) was shown to be perfectly convenient in producing good secondary beams of light elements. It was recently used for ^{11}Li [4]- or ^{20}Mg [5]-induced experiments.

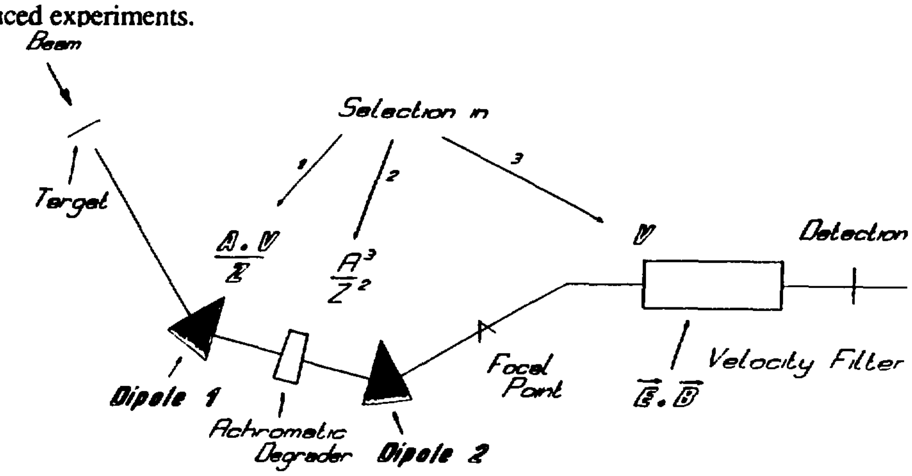

Figure 1
A schematic lay-out of the LISE spectrometer. From Ref. 3)

The large spectrometer upwards the experimental areas has also been used to select radioactive beams such as ^{14}O or ^{12}N. Their radiative capture was studied[6] to measure cross-sections of astrophysical interest. Based upon this experience, it was realised that a genuine facility delivering high-energy (greater than, say, 30 MeV/nucleon) secondary beams could be available rather rapidly at GANIL. The SISSI project[7] essentially aims at matching (Fig.2) the rather large opening (2 x 70-80 mrad) of the emission cone of the fragmentation products to the acceptance of the beam-lines, so that they can be conducted in any experimental area. To keep these products within an emittance :

$$\varepsilon_T \approx 16\,\pi \text{ mm.mrad}$$

the Liouville's theorem makes it necessary to keep the beam-spot size under the rather small value of 0.4 mm. This can be achieved using magnetic lens ; since they will be located in a very congested part of the cyclotron hall, very large magnetic fields (11 Teslas) have to be produced. The SISSI device is a set of two superconducting solenoïds ; the production target is in between. Obviously, some severe technical problems concerning the field geometry, Foucault currents in the target holder, the effect of the charged (and neutrons) particles in the superconducting coils, have to be solved. The following table gives some estimated values for selected secondary beam intensities.

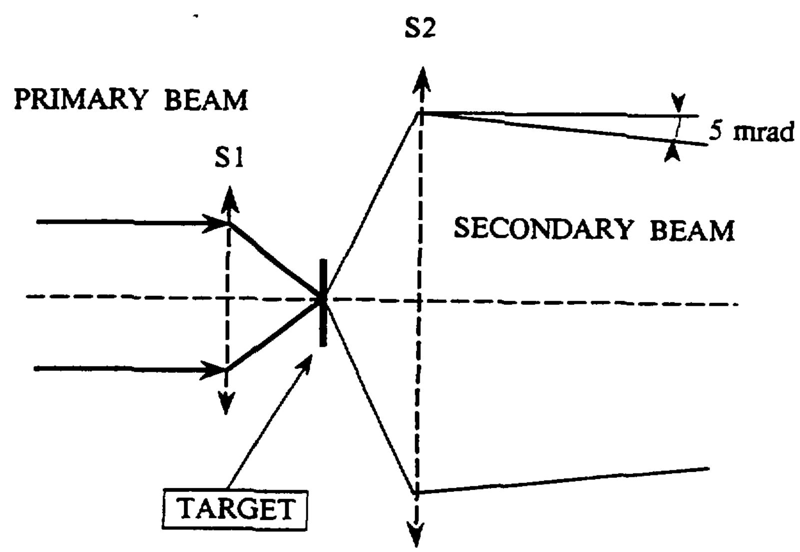

Figure 2
Principle of operation for the SISSI device.

Table 2
Intensities currently obtained with some secondary beams, and expected values using SISSI.

Ion	Current value in pps	Expected value with SISSI
^{11}Li	$2\ 10^2$	$3\ 10^4$
^{13}O	10^5	10^6
^{20}O	$2\ 10^6$	$5\ 10^7$
^{26}Na	$6\ 10^5$	10^8
^{36}Si	$8\ 10^4$	10^6
^{38}S	$5\ 10^6$	$6\ 10^7$

The solenoïds have already been coiled, and the nominal value of the field has been reached. Their acceptance tests will occur in November. The cryostat will soon be completed, and the whole system being assembled. Each solenoïd is 800 mm long, with one NbTi coil and two Nb_3Sn coils. First experiments with it are expected to take place during the fall, 1993.

4. Heavy-ion induced ISOL production of secondary beam

Recently, a strong impulse came from the french nuclear community (as well as from other ones) to boost an appreciation and evaluation of the physics opened by the availability of secondary beams. Since a large part of the physics case was concerned with low-energy beams, the ISOL method of production is clearly the favourite one. An ISOL production system, followed by a post accelerator, on one hand, and the SISSI device, on the other hand, would transform GANIL in a genuine secondary beam facility.

One should recall that producing secondaries with the ISOL method does not necessarily imply a primary proton beam. Several years ago, comparisons were performed [8)] between the production cross-sections of alcaline nuclei in high-energy proton induced reactions and intermediate energy heavy-ions, accelerated at CERN. These results (Fig.3) clearly show that the cross sections are of the same order of magnitude, with two points clearly in favour of the heavy-ion method : the isotopic distribution is definitely broader and the cross sections for proton-rich nuclei are obviousy larger in the latter case.

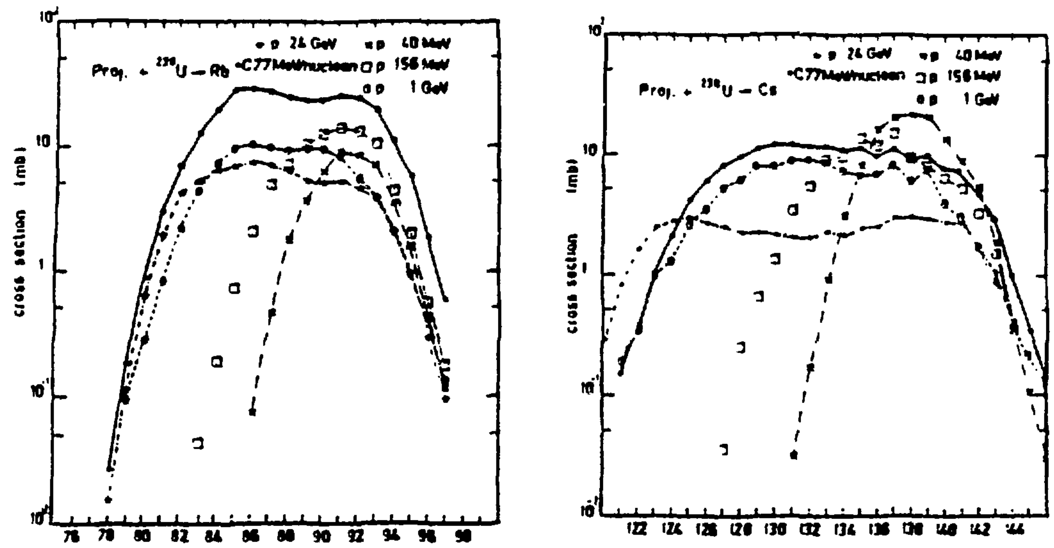

Figure 3
A comparison of production cross-sections by 85 MeV/nucleon ^{12}C projectiles and high energy protons. From Ref [8)]

A further argument is the flexibility of the choice offered by heavy ions. A definite influence of the target-projectile combination on the production cross-sections was observed[9)] at GANIL in data taken with ^{12}C, ^{40}Ar and ^{86}Kr projectiles. It appears easier to produce a ^{19}Ne beam from a ^{20}Ne one rather than from a proton beam. This feature will be essential when aiming at extreme far-from stability nuclides. To summarize, with heavy-ions, we are free to choose the optimum reaction to produce a given species.

Another important point to be discussed for the reacceleration of secondary nuclei is the charge state to which they can be ionized.A strong emphasis was given at GANIL to research and developments about ECR sources. A distinctive feature of these sources is their property of delivering multi-charged ions. To illustrate this, the Fig.4 shows the charge-state distribution obtained for Ar ions with the ECR 3 source, routinely used at GANIL. Assuming that these properties can be preserved in the production device of secondaries, a obvious advantage will be found when reaccelerating them.

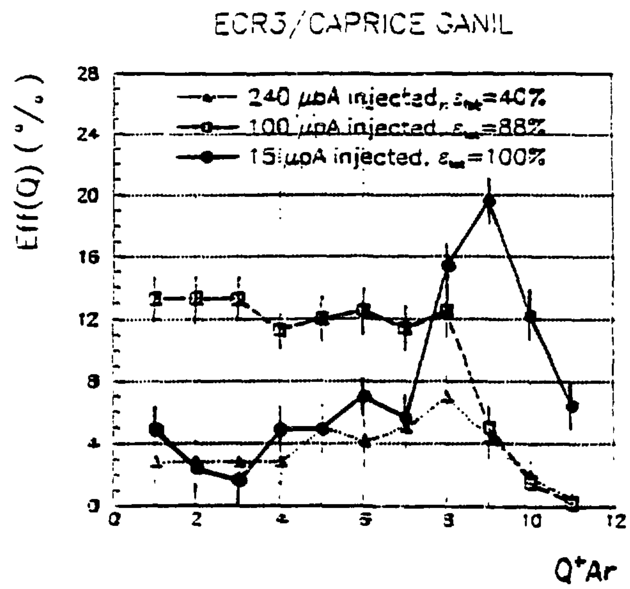

Figure 4
Charge state distribution of Ar ions, as obtained with the ECR 3 sources. From Ref. [11]

To test these properties, a test bench was set-up at GANIL, on which the thick target is closely coupled to a new and very small ECR ion source (NANOGAN), the magnetic configuration of which is obtained from permanent (Fe-Nd-B) magnets. This program was conducted, up to now, on Ne isotopes and ^{13}N. The first results obtained[10] with this experimental set-up are summarized in Table 3.These results show it possible to efficiently transport radioactive products from a heavy ion irradiated target to an ECR source. On-line efficiencies (release from the target x decay survival x ionization efficiency) as high as 10 to 20 % have been reached. Off-line efficiencies up to 30 %, measured with a calibrated argon gas leak were also observed. However, the beam optics and the geometry of the whole set-up introduced difficulties with the detection and the entrance window of the crucible. Moreover, the detection system was poorly shielded, and the ECR source had to be operated in the pulsed mode, which is very unstable. This has given, however, some important informations in the operating mode of the NANOGAN source, compared with the ECR 4 one (Fig.5). This figure shows, in particular the opposite roles of the pressure and of the injected RF power. Specifically, it is possible to balance the role of too large a pressure in the source if a larger power is brought in. The conditions under which this RF power is brougth in are highly critical, and work remains to be perform on this subject.

Table 3.

Comparison between on-line production yields, as measured on the GANIL test-bench, with the Summerer's predictions, for a 95 MeV/nucleon ^{20}Ne beam on a MgO target.

Secondary ion	Half-life	Efficieny (%)	I measured (p/s/μAp)	I predicted (p/s/μAp)
$^{19}Ne^{1+}$	17.2s	1.0	5.2 10^9	
$^{19}Ne^{2+}$	"	0.5	1.8 10^9	
$^{19}Ne^{3+}$	"	0.2	7.9 10^8	
		Σ	7.8 10^9	1.3 10^{10}
$^{18}Ne^{2+}$	17.2s	0.5	3.7 10^8	
$^{18}Ne^{4+}$	"	0.05	3.9 10^8	
		Σ	7.6 10^8	2.7 10^9
$^{23}Ne^{1+}$	37.5s	1.0	6.3 10^7	5.10^8
$^{24}Ne^{1+}$	3.38 m	1.0	1.5 10^7	1.10^8
$^{13}N^{1+}$	9.97 m	?	3.8 10^5	1.5 10^9

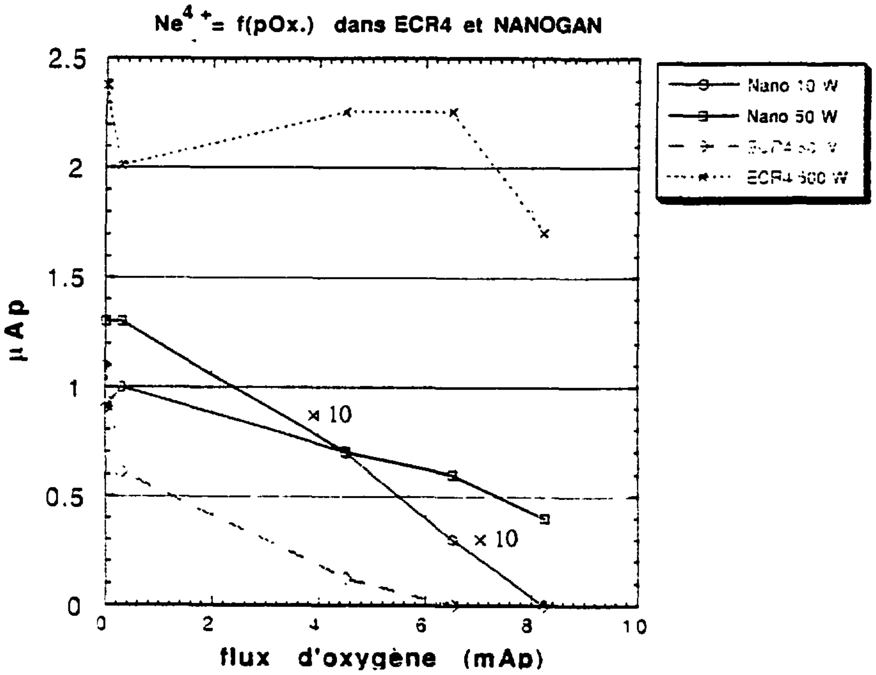

Figure 5
Comparison of the production yields for the NANOGAN and the ECR-4 ion sources, as a function of pressure and R.F. injected power.

Consequently the lines of research and development to be followed are the following. Out-gasing measurements will be obtained from hot targets. Tests will be conducted on the ECR-3 and ECR-4 sources, in which fluxes of gas will simulate outgasing conditions, to a better knowledge of their performances under relatively high pressures. To get rid of problems with the target entrance window and to optimize the detection, the experimental room will be remodeled. The current objective is still centered on the ionisation of noble gases, as well as measurements of the time delays introduced by the ionisation process, and aims to rapidly reach sufficient information for a new design of a robust and highly efficient ECR source.

5. Post-Accelerator

As already mentionned, the nuclear community has expressed a strong enthousiasm for a convenient use of radioactive beams, and they have already elaborated a rather copious menu of the experiments they could wish to perform. It is certainly not possible to satisfy the whole spectrum. However, these informations were sufficient to allow for the definition of the corresponding machine.

Several factors have to be taken into account : the available domain of physics, the cost of the accelerator and the time spent to built it, the commercial availability of parts as well as the experience of a staff of engineers and technicians, confronted to a wide range of new problems. The resulting project is described below.

This cyclotron would be a K = 262 one.The cyclotron would have a fourfold symmetery, with four poles and 2 RF resonators and a maximum size of 6,70 x 6,70 m^2. The extraction radius would be 1,5m. The maximum average value of the field will be ≈ 1.56 T. The corresponding energies as a function of mass are given on the Fig.6.

The strongest assumption of the project, apparent on the figure is the availability of rather high values of the charge to mass ratio :

$$\left(\frac{Z}{A}\right) \approx 0.15 - 0.20 \text{ for } A \cong 100$$

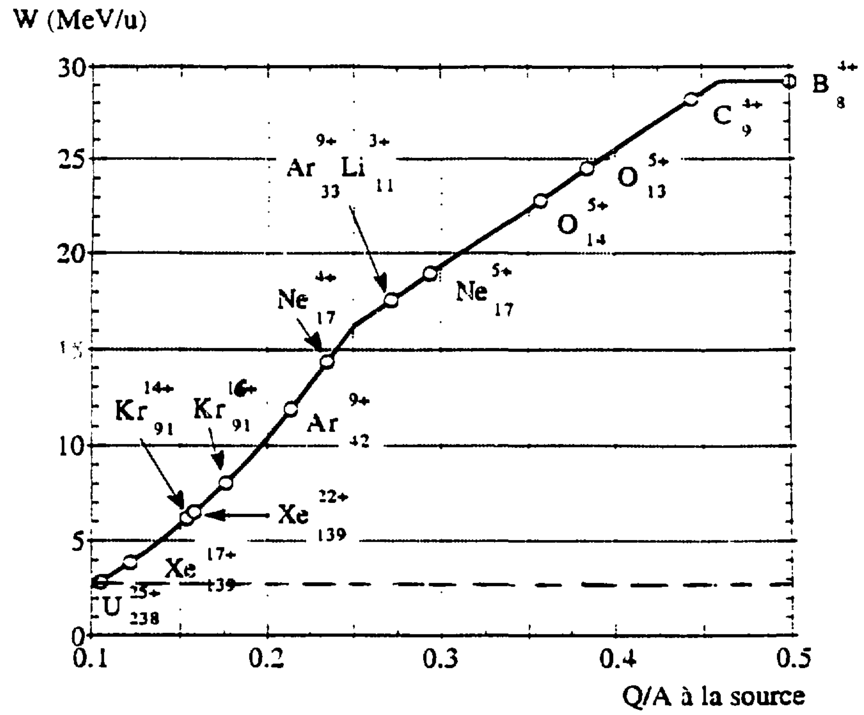

Figure 6
The available energy per nucleon as a function of the charge to mass ratio for the cyclotron discussed in text.

The curve of Fig.6 has to be explained. The lowest part of it, corresponding to larger masses, is defined by the avalaible magnetic field strength. The upper part of the graph is defined by the maximum value of the ratio frequency. As for the intermediate one, it is obtained when one wants to keep identical orbits inside the cyclotron, whatever the ion is. This curve can be summarised by the following figures :

$A \leq 12$	$E/A \leq 30$ MeV/nucleon
$20 \leq A \leq 50$	$E/A \approx 10$ MeV/nucleon
$50 \leq A \leq 100$	$E/A \approx 6$ MeV/nucleon

A minimum energy per nucleon exists, at a value of 2.7 MeV/nucleon. The expected intensities can be grossly evaluated, knowing that the axial injection yield is expected to be of the order of 0.5 - 0.6 (based upon current experience at GANIL), and using a value of 0.8 as the ejection yield of the post-accelerator.

An interest in using a cyclotron can be found from the point of view of the ion separation. Considering the phase shift along 254 turns, the mass resolution to be expected is of the order of 2-5. 10^{-4}. There is still room for a separation by energy-loss through a thin foil.

The target and source locations, as well as the room for the cyclotron, exist at the extremity of the present accelerator. Such a lay-out is very favourable, taking into account the opportunity to inject the postacceleratd secondary beams in the alpha spectrometer (for discrimination and analysis, and to find b^ck the path to the many experimental rooms. (Fig.6)

The range of energies which are considered in this project are broader than in other ones. This will be particularly helpful to make the connection with the fragmentation beams. However, the minimum value of 2.7 MeV/nucleon makes a very severe limitation for the domain of astrophysical reactions to be studied. However, expecting that the pressure of the community stays as high as it is now, a small cyclotron could be fitted close to the former one, so that its axial injection line would be purely an extension of the big cyclotron line. When expected, its beams could also be directed to the alpha spectrometer (Fig. 7). It would have a $K \approx 24$, and the diameter of its poles would be 1.2m. It would be delicated to h^ low energy domain : 0.2 to 2.9 MeV/nucleon.

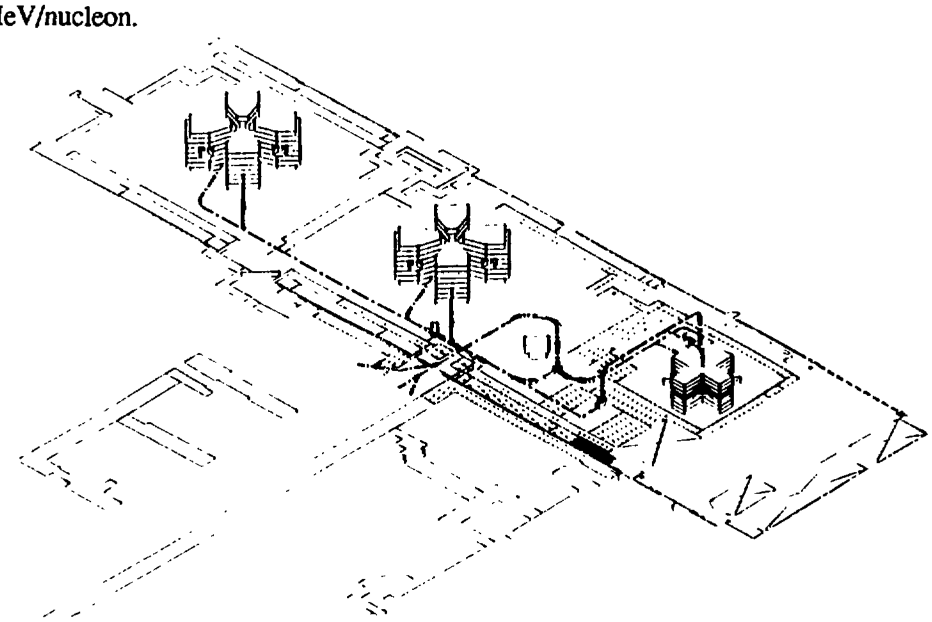

Figure 7
Lay-out of the final project.

Conclusion

Up to now, two strong fields of intermediate-energy nuclear physics have been developed at GANIL : hot nuclei studies, and production of exotic nuclei. With the more and more important use of secondary beams, it is quite likely that this balance could be displaced in favour of nuclear structure studies. The laboratory is preparing this opportunity, which would mean a larger opening of its activities, with two new devices: SISSI will deliver secondary beams, beyond 30 MeV/nucleon, as soon as September 93. The cyclotron project will provide secondary beams in a lower energy domain, where physics has already been shown extremely rich, but where the isospin degree of freedom was not fully exploited yet.

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